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An Improved Power Control Strategy for Hybrid AC-DC Microgrids

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Abstract: This paper presents a new droop-based control strategy for hybrid microgrids (HMG) with improved power sharing. When ac microgrids (AC-MG) and dc microgrids (DC-MG) are present in a distribution grid, there is an opportunity to interconnect them via an interlinking converter (IC) and form a HMG. Power sharing and adequate voltage/frequency control are the main functions of AC-MG and DC-MG control systems in standalone mode. When it comes to a HMG, active power sharing throughout the whole system must also be properly achieved by controlling the IC active power throughput. Furthermore, the possibility of participation of IC in AC-MG reactive power adds some complexity to a HMG control system. In this paper, a new decentralized control strategy is presented for a HMG which relies on regulating the voltage magnitude of a common bus in each microgrid. In this regard, new droop characteristics for sources across both microgrids as well as IC are proposed. The proposed droop characteristics result in better active/reactive power sharing across both microgrids and at the same time results in better voltage regulation. The derivation of new droop characteristics is thoroughly discussed in this paper. Simulation results are used to show the improvement achieved.

Keywords: Decentralized control strategy; distributed energy resource; hybrid microgrid; power sharing

Nomenclature

Acronyms

HMG	Hybrid microgrid
AC-MG	Ac microgrid
DC-MG	Dc microgrid
IC	Interlinking converter
MG	Microgrid
P-f	Active power-frequency
Q-V	Reactive power-voltage
I-V	Current-voltage
P-V	Active power-voltage
PI	Proportional integral
VCM	Voltage controlled method
CCM	Current controlled method
SRF	Synchronous rotating frame

AAE	Average of absolute error
BRE	Band of relative error

Variables

f_i	Frequency of the output voltage reference in the i th ac source
$V_{ac,i}$	Magnitude of the output voltage reference in the i th ac source
f_0	Frequency of AC-MG at no load
$V_{ac,0}$	Voltage of AC-MG at no load
$P_{ac,i}$	Generated active power in the i th ac source
$Q_{ac,i}$	Generated reactive power in the i th ac source
$m_{ac,i}$	Slope of P-f droop in the i th ac source
$n_{ac,i}$	Slope of Q-V droop in the i th ac source
$V_{dc,i}$	Output voltage reference in i th dc source
$V_{dc,0}$	Voltage of DC-MG at no load
$P_{dc,i}$	Generated active power in the i th dc source
$m_{dc,i}$	Slope of P-f droop in the i th dc source
f_{ic}	Frequency of IC ac bus
$f_{ic,pu}$	Per-unit frequency of IC ac bus
Δf	intended frequency variation range in AC-MG
$Q_{ac,i}$	Generated reactive power in the i th ac source
$m_{ac,i}$	Slope of P-f droop in the i th ac source
$n_{ac,i}$	Slope of Q-V droop in the i th ac source
$V_{dc,i}$	Output voltage reference in i th dc source
$V_{dc,0}$	Voltage of DC-MG at no load
$P_{dc,i}$	Generated active power in the i th dc source
$m_{dc,i}$	Slope of P-f droop in the i th dc source
f_{ic}	Frequency of IC ac bus
$V_{dc,ic}$	Voltage of IC dc bus
$V_{dc,ic,pu}$	Per-unit voltage of IC dc bus
ΔV_{dc}	intended voltage variation range in DC-MG
P_{ic}^*	Reference active power set point of IC
Q_{ic}^*	Reference reactive power generation of IC
$V_{ac,ic}$	Voltage magnitude of IC ac bus
n_{ic}	Slope of Q-V droop in IC
$V_{ac,c}$	Voltage magnitude of common ac bus
$V_{dc,c}$	Voltage of common dc bus
$V_{dc,c,pu}$	Per-unit voltage of common dc bus
$R_{dc,ic}$	Resistance of IC dc line

$I_{dc,line,ic}$	Current of IC dc line
$I_{ac,ic,dq}$	Ac-side current of converter in SRF
E_{dq}	Ac-side voltage of converter in SRF
E_{dq}^*	Reference ac-side voltage of converter in SRF
$R_{ac,ic}$	Resistance of IC ac line
$X_{ac,ic}$	Reactance of IC ac line
$R_{ac,i,eff}$	Effective output resistance of the i th ac source
$X_{ac,i,eff}$	Effective output reactance of the i th ac source
δ_i	Phase difference between voltages of the i th ac source and common ac bus
$R_{dc,i}$	Resistance of the i th dc line

1. Introduction

A microgrid (MG) is defined as a part of distribution grid including generation, storage and load which can operate either as an autonomous system with no connection to the main grid or as a part of distribution grid with some added features [1]. Typically, a MG has two modes of operation. In grid-connected mode, generation units usually inject a predetermined value of active and reactive power based on the economic and technical consideration. For example, a common practice with renewable energy resources is to inject the maximum extracted power to the grid. In this mode, also known as PQ mode, a generation unit can be modeled as a current source. In the case of any major disturbance in the main grid, MG can be disconnected and enters into the so-called islanded or standalone mode. In the islanded mode, which is the subject of this research work, supply–demand balancing along with frequency and voltage control must be invoked. One of the main challenges in this mode is to share the load among sources proportional to their KVA rating without overstressing them [1-3].

The control strategies proposed for MGs can be categorized into two groups, namely centralized and decentralized [2]. Generally, centralized control strategies rely on fast and reliable communication links among sub-systems. This makes the system inherently less reliable and prone to the loss or problematic issues in communication media. On the other hand, decentralized control strategies have proved to be more robust and reliable in distributed systems such as a MG. In this regard, the most common decentralized method proposed by the researchers and employed in MGs is droop control strategy [4-6].

Ac microgrids (AC-MGs) have been known for more than a decade. Recently dc microgrids (DC-MGs) are also becoming attractive due to the increasing penetration of dc sources and loads in distribution systems [7-9]. DC-MGs have been implemented in industrial systems, commercial buildings and residential complex [7].

When both AC-MG and DC-MG are present in a distribution system, they can be connected to form a hybrid microgrid (HMG) [10-16], and the active power supply-demand balancing can be extended to both MGs. In other words, the total required active power can be shared among the sources in both MGs. This concept results in lower chance of an overstressed source located in a MG, lower reserving capacity requirement and lower variation in sources power demand [10-12]. In a HMG, the active power exchange between AC-MG and DC-MG is carried out via an interlinking converter (IC).

Power sharing in the standalone mode of operation of a HMG has been studied by some researchers [10-13]. For sharing realization in an AC-MG, the power-frequency (P-f) and reactive power-voltage (Q-V) droop characteristics are commonly used [1-4]. In a DC-MG, both power-voltage (P-V) and current-voltage (I-V) droop characteristics have been proposed [17]. However, due to the need to coordination between two MGs in a HMG, P-V droop characteristic is usually used in DC-MG when it is a part of HMG [10-13]. For extending active power sharing to the sources of both MGs, also known as proportional active power sharing [10, 11], the IC must exchange a proper amount of active power between two MGs. In this regard, the reference active power of IC is determined based on AC-MG frequency and DC-MG voltage in order to exchange proper active power and hence proportional power sharing is achieved [10, 13, 15].

In addition to active power exchange, the IC can participate in reactive power supply of AC-MG. This results in better reactive power support and voltage quality. This participation can be accomplished by using a proper Q-V droop characteristic in IC control system [10, 18, 19].

Droop based sharing strategies, also known as primary control in hierarchical control structures [4], have some limitations. For example, whenever voltage is a part of droop characteristic realization, inaccurate sharing can occur as a result of voltage magnitude variation in a MG buses caused by line impedances [20, 21]. To reduce or eliminate this error, several attempts have been made [20-29]. In [22] and [23]. Some improvements have been made by injecting additional harmonic signal to the line. However, these invasive methods have the disadvantage of line current distortions [20]. In [21] and [24], reactive power sharing is achieved by activating an enabling signal for a specific interval. However, if load variation happens in this interval, error in reactive power sharing and stability problems could occur. In [25-27, 30], more accurate sharing is obtained using low bandwidth communication links. However, this approach must be implemented in secondary control, which results in a delay in compensation as compared to the modification methods realized in primary control.

In [28], accurate reactive power sharing between ac sources in an AC-MG where sources are radially connected to a common bus is obtained. In this study, the virtual output impedance of a source is regulated such that the total source impedance becomes inversely proportional to source capacity. This control

structure, however, can lead to lower voltage quality as a result of output impedance voltage drop. In [20], the slope of Q-V droop characteristics of ac sources are modified to compensate the voltage drop associated with source output impedance. In this study, the source output impedance voltage drop is assumed to be independent of source voltage variation, which can result in some error in reactive power sharing [24]. Similar study for providing accurate current sharing between dc sources using I-V droop characteristic has been presented in [29], but this droop characteristic is not commonly used in HMG application.

The objectives and the realization of controllers in ac and dc sources are different from those in IC. Therefore, if the classic controllers proposed in the literature for ac and dc sources are applied to IC, a desirable performance cannot be expected. Besides, the existing studies are not sufficient for handling all sharing requirements associated with a HMG. This is because of the fact that in a HMG, in addition to the need to conventional power sharing in both AC-MG and DC-MG, the participation of IC in reactive power sharing in AC-MG and proportional active power sharing throughout HMG must be properly taken into consideration. These important issues are mainly involved with IC operation. For fulfilling these two sharing concepts, the control strategy of IC must be properly modified. This subject has not been thoroughly addressed in the literature.

In this paper, a decentralized control strategy for power sharing improvement in a HMG with radially connected sources is proposed. The proposed strategy provides near-ideal sharing for reactive power among ac sources, reactive power between ac sources and IC, active power among dc sources and active power sharing throughout HMG. This is resulted by modifying the control strategy in ac sources, dc sources and specifically in IC. The proposed strategy relies on voltage regulation in a common bus in each MG. It is shown that using this approach leads to high quality regulated voltage on common buses in both MGs.

This paper is organized as follows. Section 2 explains the conventional control strategy in a HMG. The proposed control strategy is described in Sec. 3. Simulation results are presented in Sec. 4. As the proposed strategy is dependent on line parameters information, the sensitivity to error in these parameters is examined in Sec. 5. In section 6, the stability analysis of proposed strategy is presented.

2. Conventional control strategy of HMG

A typical HMG structure is shown in Fig. 1. A HMG can be structurally divided into three sub-systems, namely an AC-MG, a DC-MG and the interlinking converter, IC. The conventional decentralized control strategy proposed by researchers for AC-MG, DC-MG and IC [10, 13] is briefly explained in this section.

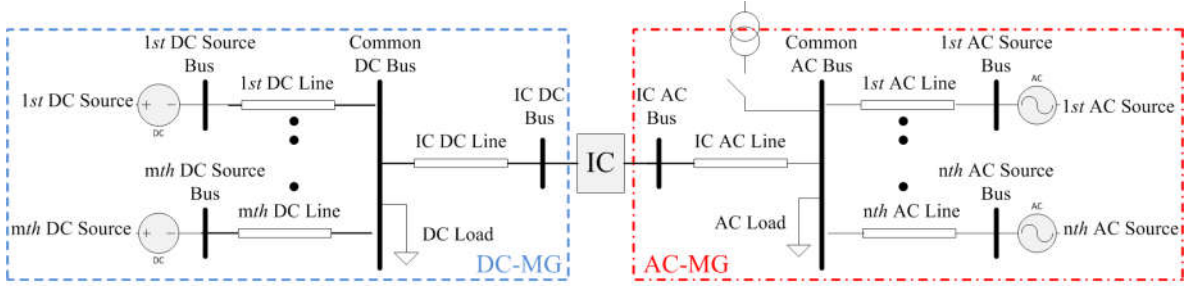


Fig. 1. The HMG structure under study

2.1. Conventional control strategy of an AC-MG

A common technique for the decentralized control of an AC-MG is to use droop characteristics [2, 4]. This technique results in proper voltage and frequency control throughout an AC-MG and power sharing among ac sources. P-f and Q-V droop characteristics for each ac sources is given by

$$f_i = f_0 - m_{ac,i} P_{ac,i} \quad (1)$$

$$V_{ac,i} = V_{ac,0} - n_{ac,i} Q_{ac,i} \quad (2)$$

where f_i and $V_{ac,i}$ are the frequency and magnitude of the output voltage reference, f_0 and $V_{ac,0}$ are the frequency and voltage at no load, $P_{ac,i}$ and $Q_{ac,i}$ are generated active and generated reactive generated powers and $n_{ac,i}$ and $m_{ac,i}$ are droop slopes in the i th ac source. In this method, f_i and $V_{ac,i}$ are realized by voltage controlled method (VCM) [31]. For proper power sharing among sources in proportion to their capacity, the slopes of droop characteristic in each source is chosen inversely proportional to its capacity [30, 32].

The presented droop control strategy is based on dominant inductive line impedances, but this requirement usually cannot be fulfilled in all AC-MGs, which results in poor dynamic performance [4, 20, 33]. This problem is overcome by implementing a virtual impedance in the source controller such that the sum of real and virtual impedances, known as effective output impedance, becomes dominantly inductive [28, 33].

2.2. Conventional control strategy of a DC-MG

The control strategy of dc sources in a typical DC-MG is less complicated. Dc sources are controlled with one droop characteristic given by (3), resulting in proper voltage control and power sharing [17].

$$V_{dc,i} = V_{dc,0} - m_{dc,i} P_{dc,i} \quad (3)$$

In (3), $V_{dc,i}$ is the output voltage reference realized by VCM, $V_{dc,0}$ is the voltage at no load, $P_{dc,i}$ is the generated active power and $m_{dc,i}$ is droop slope in the i th dc source. Similar to sources in an AC-MG, the slope of droop characteristic in each source is chosen inversely proportional to its capacity.

2.3. Conventional control strategy of IC

The IC shown in Fig. 1 connects AC- and DC-MGs to provide the opportunity for exchanging active power between them and thus extend the active power sharing throughout HMG. This task is accomplished by equalizing the per-unit active power of sources in both MGs.

Extending (1) to an AC-MG, the operation of an AC-MG at its rated power corresponds to the lowest operating frequency. The difference between the no load frequency and the lowest operating frequency can be defined as the intended frequency variation in an AC-MG, denoted by Δf . Based on this definition, Δf corresponds to the rated capacity of an AC-MG. Consequently, any frequency deviation with respect to the no load frequency can be used as an indication of the occupied capacity of an AC-MG. Based on the above explanation, the per-unit frequency in an AC-MG is defined as

$$f_{ic,pu} = \frac{f_0 - f_{ic}}{\Delta f} \quad (4)$$

where all the parameters have already been defined.

Based on (3), and in a similar fashion, the per-unit dc voltage in the DC-MG is defined as

$$V_{dc,ic,pu} = \frac{V_{dc,0} - V_{dc,ic}}{\Delta V_{dc}} \quad (5)$$

where ΔV_{dc} is the intended voltage variation range in the DC-MG.

Proportional active power sharing between two MGs can be achieved by equalizing $f_{ic,pu}$ and $V_{dc,ic,pu}$. This can be realized by employing a proportional integral (PI) controller to determine the reference power set point of IC, i.e.

$$P_{ic}^* = \left(k_p + \frac{k_i}{s} \right) (V_{dc,ic,pu} - f_{ic,pu}) \quad (6)$$

where P_{ic}^* is the reference active power set point of IC which is eventually transferred from DC-MG to AC-MG and k_p and k_i are controller coefficients.

It must be pointed out at this stage that the realization of active power control in ac sources and IC is different. Based on (1), ac sources measure the active power and consequently adjust their frequency based on their droop characteristic. This is achieved by voltage controlled method (VCM). On the other hand, IC determines its reference active power from (6), and realizes it by current controlled method (CCM).

In addition to active power exchange, an IC can participate in supplying reactive power in the AC-MG. This is similar to the participation of each ac source in supplying the total AC-MG reactive power demand. Equation (7) determines how the IC contributes in reactive power generation.

$$Q_{ic}^* = n_{ic}^{-1}(V_{ac,0} - V_{ac,ic}) \quad (7)$$

In (7), Q_{ic}^* is the reference reactive power generation of IC, $V_{ac,ic}$ is the voltage magnitude of IC ac bus and n_{ic} is droop characteristic slope which is inversely proportional to IC rated power [10, 18].

Again, it is noteworthy that although (7) and (2) are the same, but their realizations are different. In (2), i.e. in ac sources, the reactive power is measured and consequently the ac source output voltage is realized using VCM. In the IC, on the other hand, the output voltage is measured and the reference reactive power is generated. The realization is also performed by CCM [31]. Figure 2 shows the block diagram of the conventional IC control strategy.

It can be concluded that there are some differences in the objectives and realization of ac and dc sources when compared to IC control strategy, and thus adopting their control strategies for IC would result in inadequate power sharing. In the next section, it is explained how sharing issues associated with a HMG are resolved by the proposed control strategy.

3. Proposed control strategy of HMG

As shown by (2) and (3), the reactive power sharing strategy in AC-MG and active power sharing strategy in DC-MG rely on the terminal voltage magnitude of sources. Furthermore, (6) and (7) respectively show that proportional active power sharing between MGs and the participation of IC in reactive power sharing are also realized by sensing voltages at IC terminals. Using terminal voltage generally does not lead to ideal sharing, which is undesirable. This is explained in more details in the following.

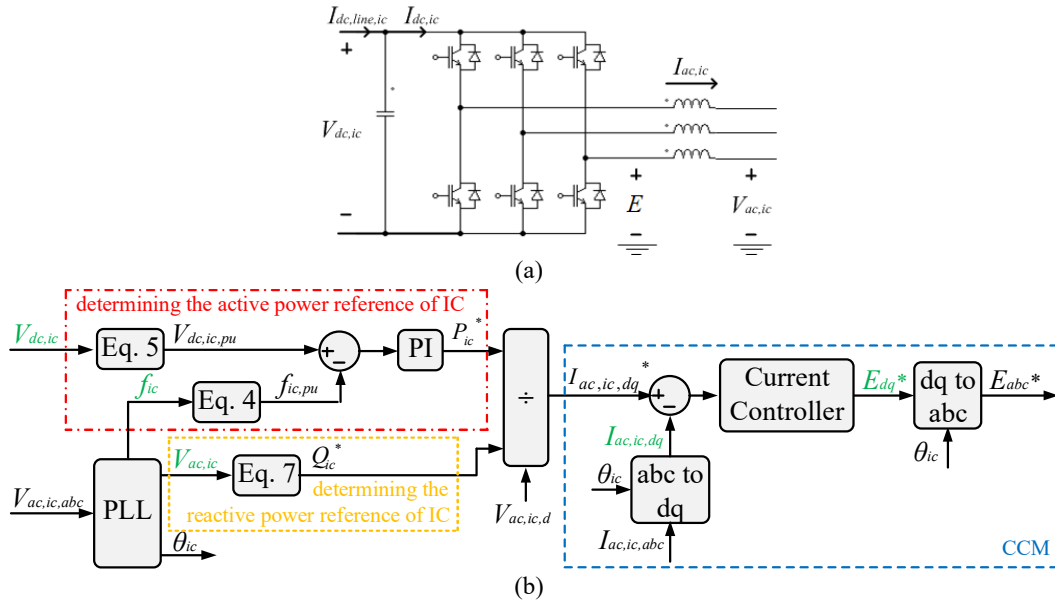


Fig. 2. (a) Topology of IC, (b) control structure of IC.

Unlike frequency, voltage is not a global parameter in a power system. In other words, different bus voltages in a typical power system are not the same due to line impedance and grid topology. Based on (2) and (7), and assuming that the per-unit value of $V_{ac,0}$ is the same for all ac sources and IC, and the per-unit value of n_{ac} and n_{ic} are also the same, unequal bus voltages in ac side will result in unequal per-unit reactive power participation of ac sources and IC, i.e. non-ideal reactive power sharing. Similarly, unequal bus voltages in dc side will result in unequal per-unit active power participation of dc sources, i.e. non-ideal active power sharing between them. Furthermore, the per-unit voltage of IC dc bus does not accurately show the per-unit active power participation of dc sources and thus implementing (6) does not lead to desirable proportional active power sharing throughout HMG.

Now consider an AC-MG with a common bus, as shown in Fig. 1. Based on the above explanation, if the voltage magnitude of common bus, $V_{ac,c}$, is used in (2) and (7) for the implementation of droop characteristic in each ac source and IC, then the per-unit deviation of voltage in each source and IC with respect to $V_{ac,0}$ would always be the same, and as a result the per-unit reactive power participation of all sources and IC would be equal. In other words, ideal reactive power sharing can be realized. This argument can be similarly employed for the dc side of HMG in order to provide ideal active power sharing among dc sources and also throughout HMG.

The proposed control strategy of ac and dc sources and IC in this paper has been inspired from the above perception. Specifically, instead of employing the terminal voltage of each source (or IC) in their corresponding controllers, the voltage of common ac and dc buses are used. Therefore, (2), (3), (6) and (7) are respectively modified as

$$V_{ac,c} = V_{ac,0} - n_{ac,i} Q_{ac,i} \quad (8)$$

$$V_{dc,c} = V_{dc,0} - m_{dc,i} P_{dc,i} \quad (9)$$

$$P_{ic}^* = \left(k_p + \frac{k_i}{s} \right) (V_{dc,c,pu} - f_{ic,pu}) \quad (10)$$

$$Q_{ic}^* = n_{ic}^{-1} (V_{ac,0} - V_{ac,c}) \quad (11)$$

where $V_{dc,c}$ is the voltages of common dc bus, as shown in Fig. 1.

One should note that the implementation of (8), (9), (10) and (11) is not straightforward in a MG with decentralized control strategy, as common bus voltages are not accessible. In the following sections, it is explained how the proposed control strategy is implemented to achieve ideal power sharing.

3.1. Proposed IC control strategy

It was explained in Sec. 2.3 that IC terminal voltages are used in IC control strategy. In this section, it is explained how this approach is modified by employing the common bus voltages of both ac and dc sides in order to achieve ideal sharing.

3.1.1 Dc Side Modification

Considering Fig. 1, the voltage of common dc bus can be obtained as

$$V_{dc,c} = I_{dc,line,ic} R_{dc,ic} + V_{dc,ic} \quad (12)$$

where $R_{dc,ic}$ and $I_{dc,line,ic}$ are the resistance and current of IC dc line respectively. Using power balance in IC yields

$$I_{dc,ic} V_{dc,ic} = E_d I_{ac,ic,d} + E_q I_{ac,ic,q} \quad (13)$$

where $I_{ac,ic,d}$, $I_{ac,ic,q}$ are ac-side current in synchronous rotating frame (SRF) and E_d and E_q are ac-side converter voltage in SRF. E_d and E_q are related to the reference voltages E_d^* and E_q^* by

$$E_d = k_m E_d^* V_{dc,ic}, E_q = k_m E_q^* V_{dc,ic} \quad (14)$$

where k_m is a constant depending on modulation strategy. Substituting (14) and (13) in (12) yields

$$V_{dc,c} = (E_d^* I_{ac,ic,d} + E_q^* I_{ac,ic,q}) k_m R_{dc,ic} + V_{dc,ic} \quad (15)$$

The dc-side common bus voltage can be calculated based on (15). Figure 3a shows the proposed strategy for active power reference determination based on (15).

3.1.2 Ac Side Modification

Based on Fig. 1, the ac-side common bus voltage can be obtained as

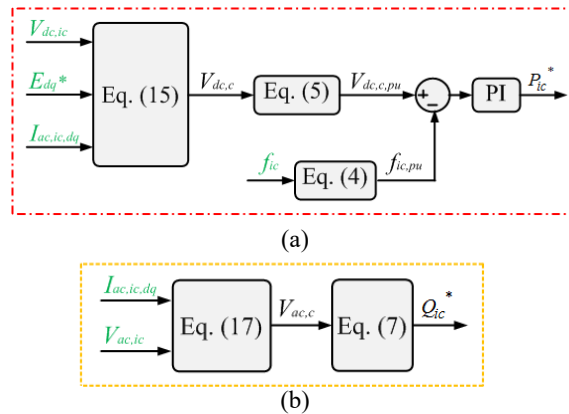


Fig. 3. (a) Proposed strategy for IC active power reference determination, (b) proposed strategy for IC reactive power reference determination.

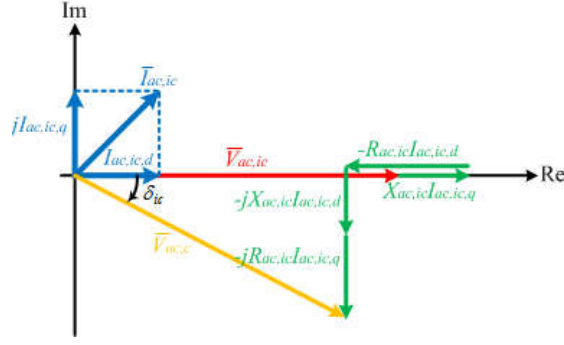


Fig. 4. Corresponding phasor diagram of (16)

$$\bar{V}_{ac,c} = -(I_{ac,ic,d} + jI_{ac,ic,q})(R_{ac,ic} + jX_{ac,ic}) + \bar{V}_{ac,ic} \quad (16)$$

where $R_{ac,ic}$ and $X_{ac,ic}$ are the resistance and reactance of IC ac line, respectively, and the bar sign denotes phasor quantities. The corresponding phasor diagram is shown in Fig. 4. Based on this diagram, the voltage magnitude of common ac bus, $V_{ac,c}$, can be expressed as

$$V_{ac,c} = \sqrt{(V_{ac,ic} - R_{ac,ic}I_{ac,ic,d} + X_{ac,ic}I_{ac,ic,q})^2 + (-R_{ac,ic}I_{ac,ic,q} + X_{ac,ic}I_{ac,ic,d})^2} \quad (17)$$

Figure 3b shows the proposed strategy for reactive power reference determination based on (17).

3.2. Ac sources control strategy

The conventional control strategy for ac sources in an AC-MG is based on VCM, as described in Sec. 2.1. In this strategy, each ac source controls its terminal voltage and participates in supplying AC-MG power employing proper droop characteristics. In this section, it will be shown how this strategy is modified such that each ac source attempts to regulate the voltage of common ac bus instead of regulating its own terminal voltage.

As stated in Sec. 2.1, ac sources usually employ virtual impedance to improve their dynamic performance [33]. The power flow between the i th ac source and common ac bus can be expressed as

$$P_{ac,i} = \frac{R_{ac,i,eff}(V_{ac,i}^2 - V_{ac,i}V_{ac,c}\cos\delta_i) + X_{ac,i,eff}V_{ac,i}V_{ac,c}\sin\delta_i}{R_{ac,i,eff}^2 + X_{ac,i,eff}^2} \quad (18)$$

$$Q_{ac,i} = \frac{X_{ac,i,eff}(V_{ac,i}^2 - V_{ac,i}V_{ac,c}\cos\delta_i) - R_{ac,i,eff}V_{ac,i}V_{ac,c}\sin\delta_i}{R_{ac,i,eff}^2 + X_{ac,i,eff}^2} \quad (19)$$

where $R_{ac,i,eff}$ and $X_{ac,i,eff}$ are the effective output resistance and reactance of the i th ac source and δ_i is the phase difference between voltages of the i th ac source and common ac bus. Assuming small δ_i , then $\sin\delta_i = \delta_i$ and $\cos\delta_i = 1$. After some manipulations, one can write

$$V_{ac,c} = V_{ac,i} - \frac{P_{ac,i}R_{ac,i,eff} + Q_{ac,i}X_{ac,i,eff}}{V_{ac,i}} \quad (20)$$

Now by replacing $V_{ac,c}$ from (20) in (8), the reference voltage of an ac source in terms of $P_{ac,i}$ and $Q_{ac,i}$ is obtained as

$$V_{ac,i} = \frac{V_{ac,0} - n_{ac,i}Q_{ac,i} + \sqrt{(V_{ac,0} - n_{ac,i}Q_{ac,i})^2 + 4P_{ac,i}R_{ac,i,eff} + 4Q_{ac,i}X_{ac,i,eff}}}{2} \quad (21)$$

Equation (21) expresses the modified droop characteristic used for ac sources to achieve ideal power sharing in AC-MG.

HMGs require a large range of frequency variation at their ac side for proper operation [10, 11]. A large range of frequency variation implies a high-slope droop characteristics, which in turns results in poor dynamic performance [34]. Therefore, the implementation of virtual inductance, which is common in AC-MGs, is even more crucial in HMGs in order to improve the dynamic performance. Based on this argument, the effective output impedance of ac sources in this application is considered inductive and consequently the ac sources voltage droop characteristic can be simplified as

$$V_{ac,i} = \frac{V_{ac,0} - n_{ac,i}Q_{ac,i} + \sqrt{(V_{ac,0} - n_{ac,i}Q_{ac,i})^2 + 4Q_{ac,i}X_{ac,i,eff}}}{2} \quad (22)$$

3.3. Dc sources control strategy

Similar to what was explained in Sec. 3.2, the control strategy of dc sources must also be modified such that an ideal power sharing is achieved in DC-MG. In doing so, each source attempts to regulate the common dc bus instead of regulating its own bus. In this regard, the active power flow equation of dc sources is given by

$$P_{dc,i} = \frac{V_{dc,i}^2 - V_{dc,i}V_{dc,c}}{R_{ac,i}} \quad (23)$$

where $R_{dc,i}$ is the resistance of the i th dc line. Replacing $V_{dc,c}$ from (23) in (9), the modified droop characteristic of dc sources is obtained as

$$V_{dc,i} = \frac{V_{dc,0} - m_{dc,i}P_{dc,i} + \sqrt{(V_{dc,0} - m_{dc,i}P_{dc,i})^2 + 4P_{dc,i}R_{dc,i}}}{2} \quad (24)$$

As can be seen from (15), (17), (21) and (24), the proposed strategy of HMG requires information about lines parameters. This information is usually available to the MG operator. Otherwise, these parameters can be obtained by different online measurement methods proposed by the researchers [20, 28, 29, 35, 36]. As the line impedance does not significantly vary over time, it is sufficient to use the

measurement method only in short interval. Therefore, even using invasive measurement methods do not affect the normal operation of the system. Further discussion on these measurement methods is out of the scope of this paper.

3.4. Voltage quality improvement

In the proposed control strategy, instead of employing the terminal voltage of each source and IC in their sharing controllers, the voltage of common ac and dc buses are used. This strategy not only provides accurate power sharing, but also results in less voltage drop in common buses especially in heavily loaded conditions. The reason behind this voltage quality improvement is bypassing line impedance voltage drop that can be considerable in heavily loaded conditions. This will be observed in simulation studies.

4. Simulation results

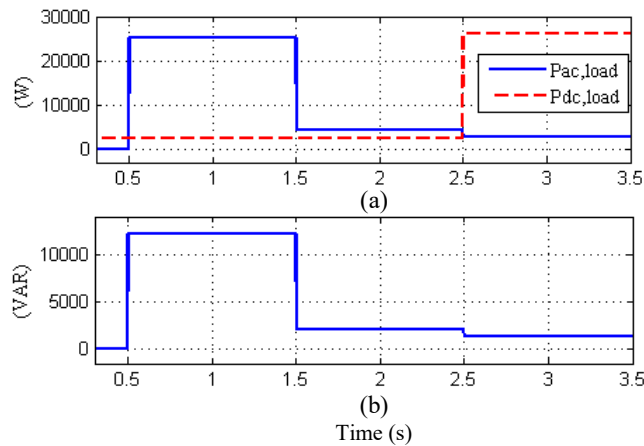
The performance of the proposed control strategy was evaluated by the time domain simulation of the islanded HMG shown in Fig. 1 with two ac sources and two dc sources. This structure will be considered in the rest of the paper. Table 1 shows the parameters of this HMG. To investigate the performance of the proposed controller in different operating points, a load variation scenario as shown in Fig. 5 is imposed to the system.

Figure 6 shows the simulation results when conventional control strategy is used. The per-unit active power participation of ac and dc sources and the per-unit reactive power participation of ac sources and IC are shown respectively in Fig. 6a and b. Error in active and reactive power sharing can be observed. The per-unit voltages in AC-MG and DC-MG are also shown in Fig. 6c and d. As stated in Sec. 2.1 and 2.3, the reactive power sharing is dependent on the terminal voltage of each source and IC in AC-MG. The correspondence between the per-unit reactive power generations and the per-unit terminal voltages can be observed from Fig. 6b and c. Again as stated in Sec. 2.2 and 2.3, the active power sharing is dependent on the terminal voltage of each source in DC-MG and frequency in AC-MG while IC coordinates its dc-side voltage and ac-side frequency. The correspondence between the per-unit active power generations and the per-unit terminal voltages in DC-MG and frequency in AC-MG can be observed from Fig. 6a, d and e.

Figure 7 shows the simulation results when the proposed control strategy is used. The per-unit active power participations of ac and dc sources are equal which verifies accurate active power sharing. In addition, the per-unit reactive power participation of ac sources and IC are shown in Fig. 7b which verifies accurate

Table 1 Parameters of the test HMG

$f_0, \Delta f$	60.8 Hz, 1.6 Hz
$V_{ac,0}, \Delta V_{ac}$	218 V, 20 V
1st and 2nd AC Source	$P_{rated}=10$ kW, $Q_{rated}=5$ kVAR, $L_v=0.8$ mH, $m_{ac}=0.0002$ 1/(s.W), $n_{ac}=0.004$ V/VAR filter: $L=0.96$ mH, $C=78$ μ F voltage controller: $kp=0.52$, $ki=344.6$ current controller: $kp=14.4$, $ki=110853$
1st AC Line	$R=0.12$ Ω , $L=0.12$ mH
2nd AC Line	$R=0.06$ Ω , $L=0.06$ mH
IC AC Line	$R=0.1$ Ω , $L=0.1$ mH
$V_{dc,0}, \Delta V_{dc}$	483 V, 46 V
1st and 2nd DC Source	$P_{rated}=10$ kW, $n_{dc}=0.0046$ V/VAR filter: $L=6$ mH, $C=12.5$ μ F voltage controller: $kp=0.125$, $ki=41.7$ current controller: $kp=56$, $ki=431000$
1st DC Line	$R=0.5$ Ω , $L=0.125$ mH
2nd DC Line	$R=0.2$ Ω , $L=0.05$ mH
IC DC Line	$R=0.4$ Ω , $L=0.1$ mH
IC	$P_{rated}=16$ kW, $Q_{rated}=8$ kVAR ac side filter: $L=5$ mH dc side filter: $C=2$ mF per-unit value controller: $kp=1800$, $ki=180000$ current controller: $kp=6$, $ki=352$ PLL controller: $kp=5$, $ki=38460$
Low-pass filter cut-off frequency of droop characteristics: 30 rad/s	

**Fig. 5.** Load variation scenario; (a) AC-MG and DC-MG active power demand, (b) AC-MG reactive power demand.

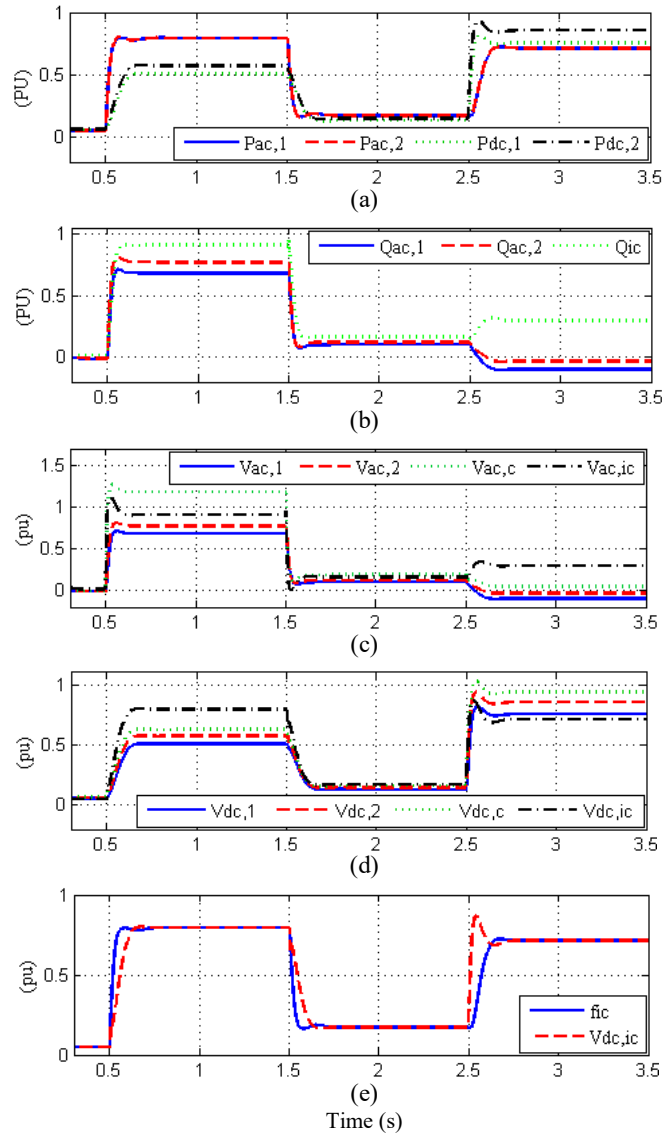


Fig. 6. Simulation results of the test HMG with conventional control strategy; (a) the per-unit active power participation of sources, (b) the per-unit reactive power participation of ac sources and IC, (c) the per-unit voltages in AC-MG, (d) the per-unit voltages in DC-MG, (e) the per-unit voltages of IC dc bus and the per-unit frequency of IC ac bus.

reactive power sharing. As stated in Sec. 3, sources and IC use the voltage of common ac and dc buses in their sharing controllers. This strategy can be investigated according to Fig. 7a to e.

Figure 8 shows the voltage of common buses when conventional control strategy and proposed control strategy are used. As can be seen, the proposed control strategy provides less voltage drop at common buses.

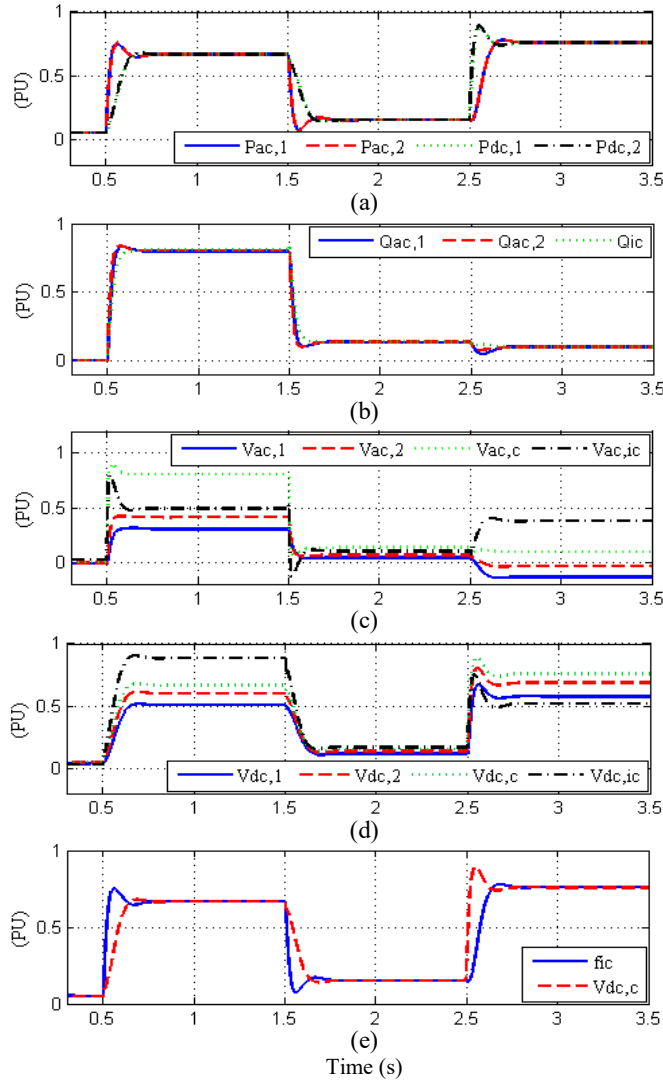


Fig. 7. Simulation results of the test HMG with proposed control strategy; (a) the per-unit active power participation of sources, (b) the per-unit reactive power participation of ac sources and IC, (c) the per-unit voltages in AC-MG (d) the per-unit voltages in DC-MG, (e) the per-unit voltages of IC dc bus and the per-unit frequency of IC ac bus.

5. Sensitivity analysis

The proposed control strategy requires information about lines parameters. In this section, the sensitivity of the proposed control strategy to the error in the measurement of lines parameters is examined.

For the quantification of error, the average absolute error (AAE) of active and reactive power in different sources and IC is considered. The maximum AAE is calculated when system parameters are varied within a band of relative error (BRE) when the system operates at its rated load. This can provide an idea about the sensitivity of sharing to parameter accuracy.

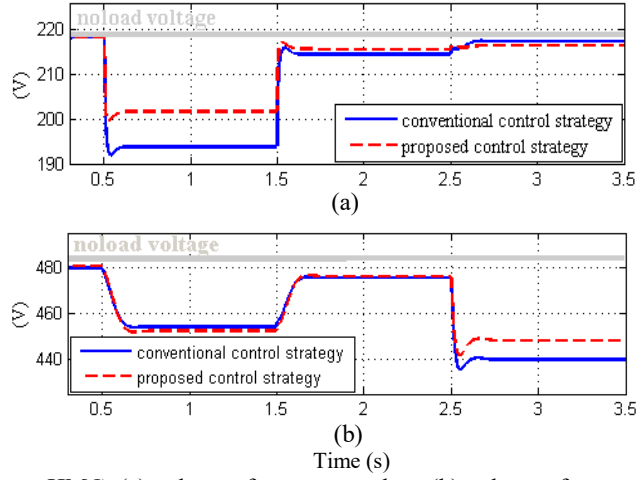


Fig. 8. Simulation results of the test HMG; (a) voltage of common ac bus, (b) voltage of common dc bus.

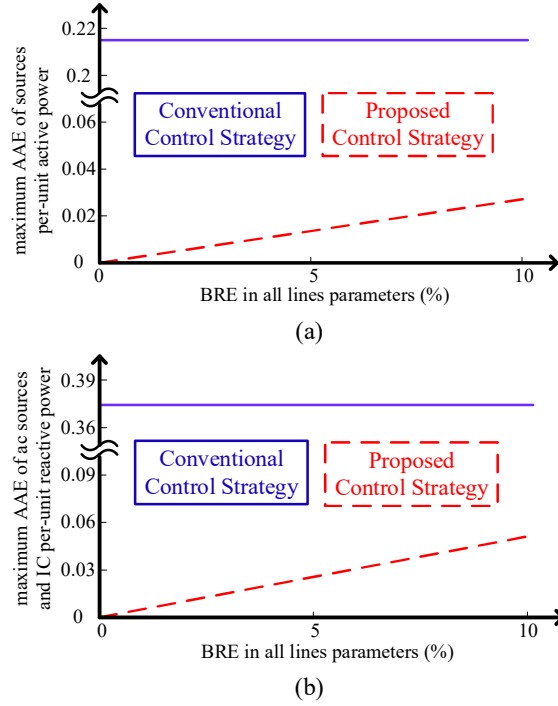


Fig. 9. Maximum AAE versus BRE for; (a) sources per-unit active power, (b) ac sources and IC per-unit reactive power.

Fig. 9 illustrates the variation of maximum AAE for sources per-unit active power and for ac sources and IC per-unit reactive power when the band of relative error changes from 0 (i.e. no error in any parameter) to 10% (i.e. the maximum relative error in different parameters is 10%). As can be seen, the maximum AAE is relatively small, showing that change in system parameters does not significantly deteriorate sharing performance. The AAE associated with conventional controllers is also shown in Fig. 9.

6. Small Signal Stability

This section deals with the small-signal stability analysis of a HMG equipped with the proposed control strategy. The derivation of small-signal model is an important task and was carried out in this research based on the methods presented in [33, 34, 37]. The modelling procedure is not elaborated in this paper though and only the results are shown. Figure 10 shows all eigenvalues associated with the HMG under study. As can be seen, the eigenvalues are on left half plane, showing that the system is stable.

The impact of some parameters on system stability was studied using root locus method. Figure 11 shows the root locus of dominant eigenvalues when the intended voltage and frequency variation ranges and the line parameters are changed. As can be seen, any increase in the intended frequency variation range in AC-MG results in decrease in S1 and S2 damping and any increase in the intended voltage variation range in DC-MG results in decrease in S3 and S4 stability. In addition, increasing ac lines reactance results in increase in S1 and S2 damping and increasing ac lines resistance deteriorates the stability of S1 and S2. This is in agreement with the discussions presented in Sec. 2.1. Finally, the increase of dc lines resistance results in improvement in S3 and S4 stability.

7. Conclusion

In this paper, a control strategy for improving power sharing in a HMG was presented. Reactive power sharing in an AC-MG (with Q-V droop characteristic) and active power sharing in a DC-MG (with P-V droop characteristic) all suffer from some error due to the fact that bus voltages are local parameters and could be different from bus to bus. In the proposed strategy, the reactive power sharing in the AC-MG is performed based on the voltage of a common ac bus. Similarly, active power sharing in the DC-MG is

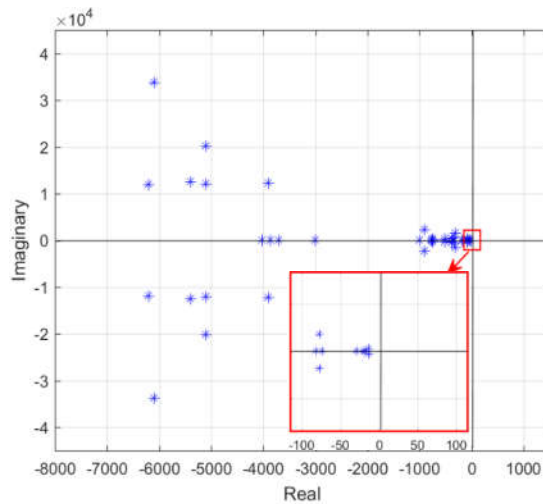


Fig. 10. Eigenvalues associated with the HMG under study.

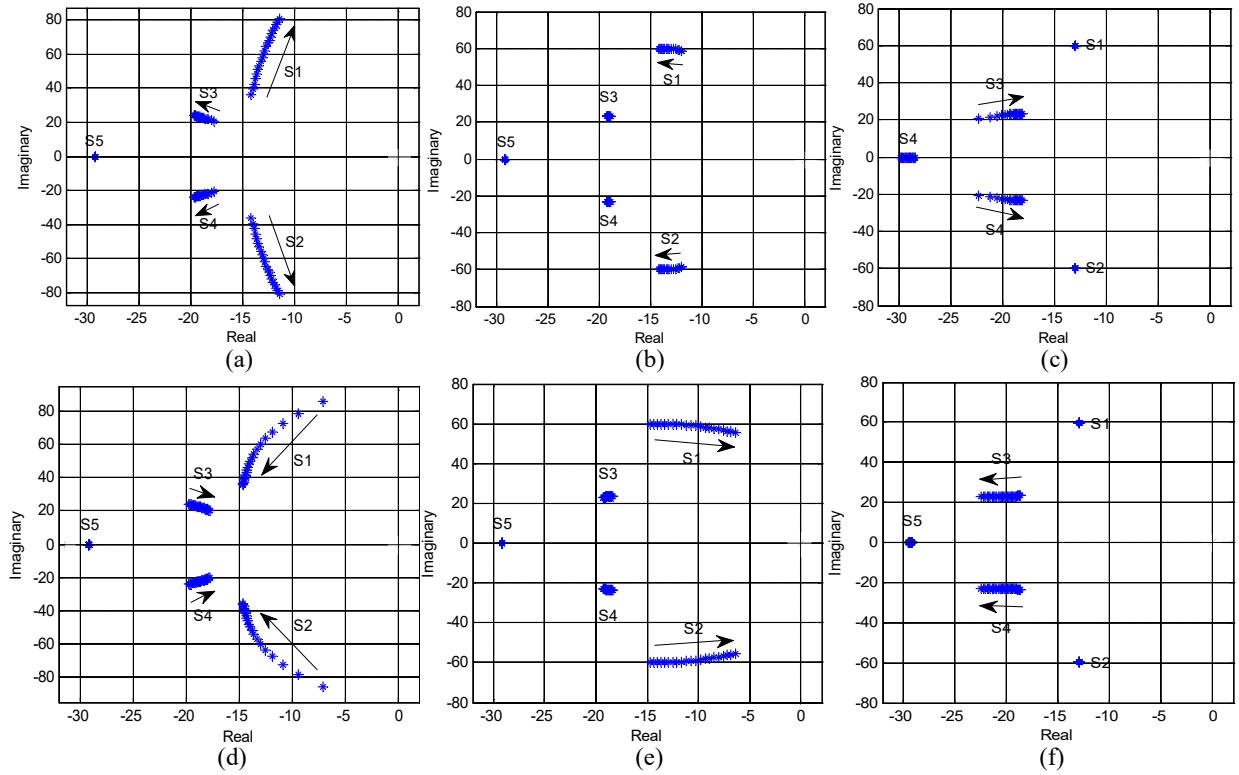


Fig. 11. System root locus versus; (a) intended frequency variation range in AC-MG from 1% to 4.5%, (b) intended voltage variation range in AC-MG from 4% to 20%, (c) intended voltage variation range in DC-MG from 4% to 20%. (d) ac lines reactance from 0.4 times to 2.5 times, (e) ac lines resistance from 0.4 times to 2.5 times, (f) dc lines resistance from 0.4 times to 2.5 times.

carried out using the voltage of a common dc bus. It was shown that how by selecting proper droop characteristics, near ideal power sharing can be achieved. The modifications made to the interlink converter (IC) control system in order to implement the proposed strategy was explained. The appropriate droop characteristics for ac and dc sources were derived. A sensitivity analysis was presented to investigate the performance of the proposed strategy due to error in the line parameters information. Simulation results were presented to verify the analysis and the improvements resulted from the proposed strategy. The small-signal stability of the test HMG with the proposed control strategy was analyzed.

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